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90^{O} BREMSSTRAHLUNG SOURCE TERM PRODUCED IN THICK TARGETS BY 50 MEV TO 10 GEV ELECTRONS

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The 90^{o} bremsstrahlung source terms produced in thick targets were studied using the EGS4 and FLUKA Monte Carlo codes. Calculations were performed for cylindrical targets of aluminum, iron, copper and lead. In the calculations, the electron beam energies varied from 50 MeV to 10 GeV, and the target radii varied from 0.5 to 3 Moliere units. The results were compared with the SLAC SHIELD11 code.

KEYWORDS: radiation shielding, bremsstrahlung, spectra, source terms, EGS4, FLUKA, Monte Carlo code, aluminum target, copper target, iron target, lead target, SHIELD11

I. Introduction

In the radiation shielding design for electron accelerator facilities, one scenario to be considered is beam losses due to mis-steering situations; e.g., a beam hits a flange or a beam pipe at a glancing angle. This situation is normally simplified as a beam hitting a thick target (the thickness of the target is greater than 20 radiation lengths (rl)). The resultant 90^{o} bremsstrahlung that leaks out of the target is one of several source terms, studies of which are available from several references[1-5]. However, this wide-angle photon source has not been extensively studied in terms of beam energy and target radii. This paper presents results using the EGS4 and FLUKA Monte Carlo codes to study these functions. In the calculations, the electron beam energies varied from 50 MeV to 10 GeV, and the target radii varied from 0.5 to 3 Moliere units*.

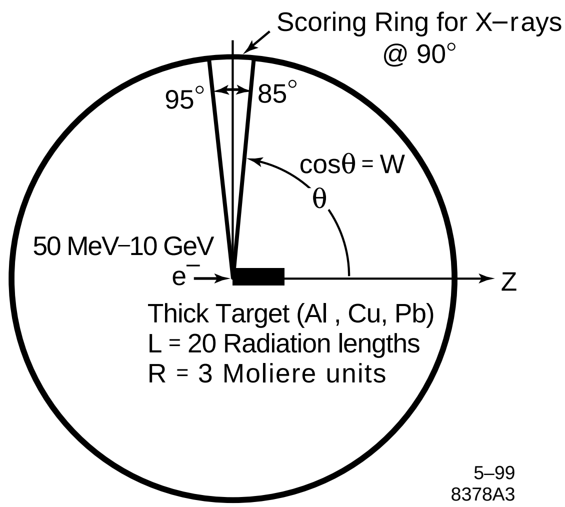

Fig. 1 Spherical geometry used in EGS4 calculations

II. Method

1. Studies of 90^{o} Bremsstrahlung Spectra

The 90^{o} bremsstrahlung spectra produced in thick targets were studied using the EGS4 Monte Carlo code[6]. Figure 1 shows the spherical geometry used in the calculations. Three cylindrical targets composed of aluminum, copper, and lead were studied. The thicknesses of targets were all 20 radiation lengths (178, 28.6 and 11.2 cm for aluminum, copper, and lead, respectively) and the radii were all three Moliere units (11.1, 3.69 and 3.75 cm for aluminum, copper, and lead, respectively). The energies of incident electron beams used in the calculations were 50 MeV, 100 MeV, 1 GeV and 10 GeV.

A scoring ring, with an angle of θ from 85^{o} to 95^{o} relative to the incident beam direction, was located at a distance equal to twenty times the target thickness from the beam incident point. The photon fluence passing through the ring was scored. The energy cutoffs were 100 keV for charged particles and 10 keV for photons.

2. Calculations of Source Terms

90^{o} bremsstrahlung source terms produced in thick targets (20 r.l. thick) were calculated by the FLUKA Monte Carlo code[7] using the cylindrical geometry shown in Figure 2. Iron targets (20 rl = 35.2 cm) were included in the FLUKA calculations, in addition to the aluminum, copper, and lead targets mentioned above.

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*The Moliere unit is the characteristic measure for radial distributions in analytic shower theory and is equal to X_oE_s/ε_o, where X_o is the target thickness, ε_o is the critical energy of the target material and E_s = 21.2 MeV.

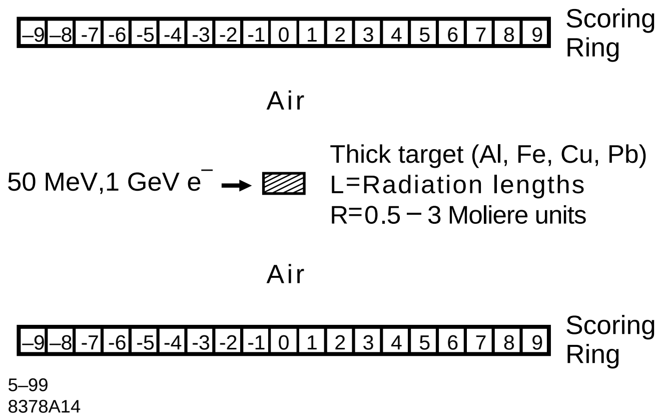

Fig. 2 Geometry used in FLUKA calculations.

The source terms as the function of target radii were studied and the target radii varied from 0.5 to 3 Moliere units. The energies of incident electron beams used in the calculations were 50 MeV and 1 GeV.

A scoring ring having nineteen segments (from –9 to +9) was located at a distance equal to twenty times the target thickness from the incident beam line. Segment 0 was located where the center of segment 0 faced to the center of the target. The length of a segment was equal to one half of the target length, and its radial thickness was 1 cm. All regions, except the target, were filled with air. 90° photon fluence was scored using the track-length scored in segment 0 divided by its volume. The photon fluence was converted to the absorbed dose in air by use of its mass absorption coefficient [8]. The source terms were expressed as absorbed dose rates per unit beam power at a distance of 1 meter from the target in unit of Gy-m^2-h^{-1}-kW^{-1}.

III. Results and Discussion

1. 90° Bremsstrahlung Spectra

The EGS4-generated spectra shown in Figure 3 indicate that the bremsstrahlung spectra at 90°, produced in thick targets by electron beams, have two important characteristics: 1) the shapes of the spectra are independent of primary electron energy over the range from 50 MeV to 10 GeV, 2) 99.9% of the photons have energies smaller than 10 MeV.

To better understand the first characteristic, the EGS4 code was also used to study the direction, W=cos θ (Fig.1), of all progeny produced inside a thick copper target. The energies of incident electron beams were 50 MeV and 10 GeV. Figure 4 shows the average W distributions of the progeny as a function of their energies. The progeny directions are seen to remain very forward directed until their energies are less than 50 MeV. This provides an explanation for why the shapes of bremsstrahlung spectra at 90° appear to be the same for primary electrons of 50 MeV or higher.

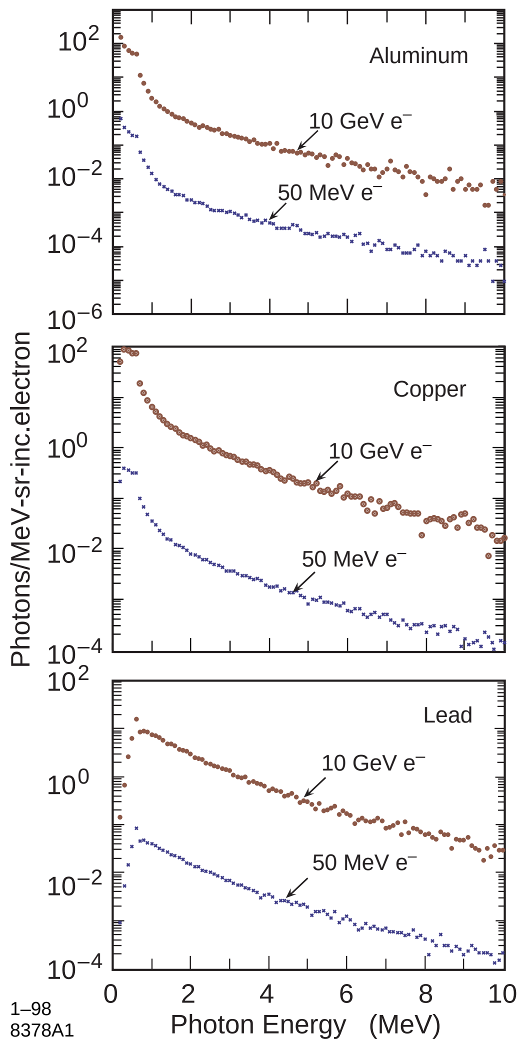

Fig. 3 90° bremsstrahlung spectra.

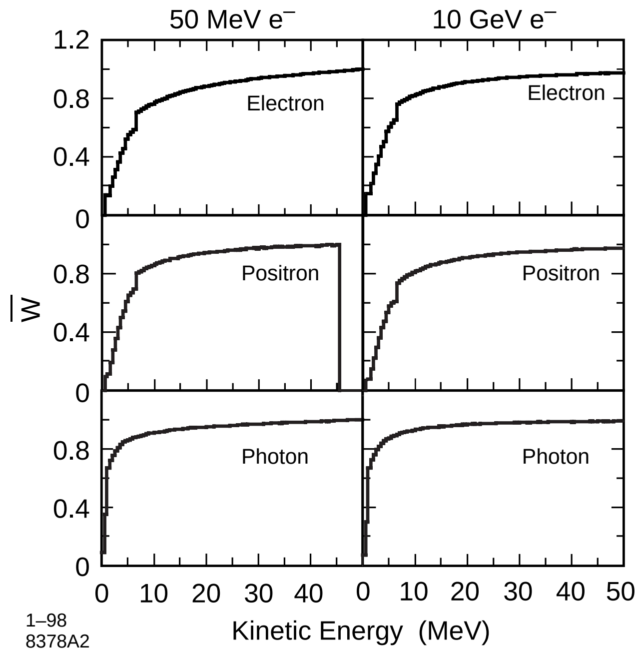

Fig 4. Progeny direction as a function of progeny energies

To understand the second characteristic, the EGS4 code was used to create a sequence table; that is, a detailed record of the production and transport of the progeny leading to the photons scored at 90^o.

From a set of sequence tables, mechanisms leading to the production of photons at 90^o were studied. It was found that the last interactions resulting in photons that are scored at 90^o are as follows:

a. most of the photons, having energies less than 1.5 MeV, are produced by Compton scattering;

b. most of the photons, having energies between 1.5 and 10 MeV, are produced by small-angle bremsstrahlung emitted by secondary electrons that have multiple scattered to large angles;

c. photons having energies of 0.511 MeV are produced by annihilation.

2. 90^o Bremsstrahlung Source Terms

Figures 5 and 6 show 90^o bremsstrahlung source terms, expressed in the unit of $Gy\text{-}m^2\text{-}h^{-1}\text{-}kW^{-1}$, produced in aluminum and lead targets by 50 MeV and 1 GeV electron beams. The FLUKA calculation errors are less than ± 5%. The results show that the source terms produced in thick targets with the same materials and the same radii are identical within the calculation uncertainty regardless of the primary electron beam energy, which agrees with the spectral studies using the EGS4 code.

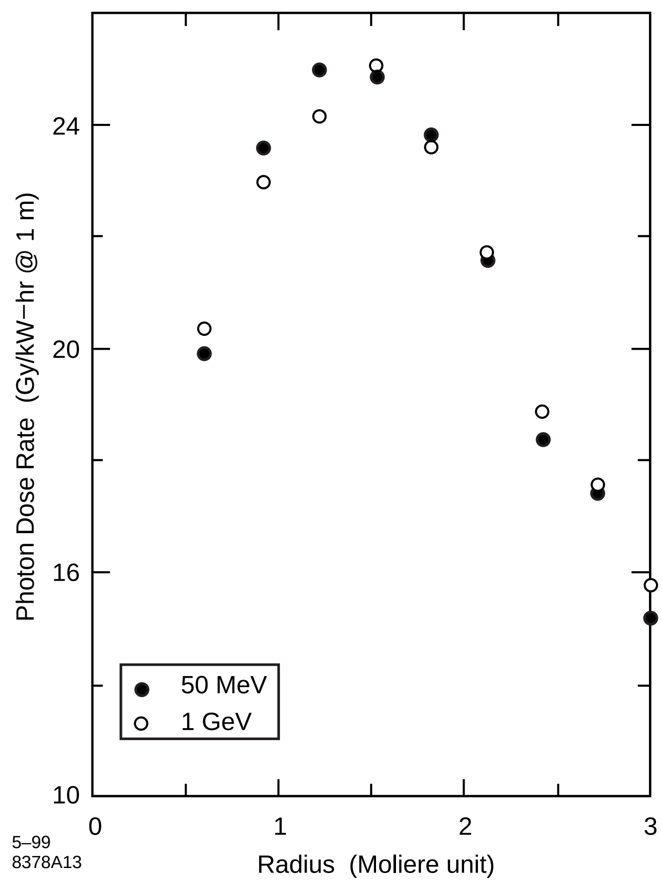

Fig. 5 90^o bremsstrahlung source terms produced in thick aluminum targets by 50 MeV and 1 GeV e^- beam

The shape of Figures 5 and 6 can be explained as follows. As the target radius increases from zero, the electromagnetic cascade shower continues to develop and the 90^o bremsstrahlung component increases. At the same time, the attenuation of photons by the target increases as the radius increases until the attenuation dominates.

Figures 7, 8, 9 and 10 show the FLUKA calculation results of 90^o bremsstrahlung from thick aluminum, iron, copper, and lead targets. The statistical errors are less than ± 5%. Based on the previous spectral studies, the source terms should be independent of the energies of the primary electrons over the energy range from 50 MeV to 10 GeV. The maximum source terms were 25, 43, 47, 73 Gy-m^2-h^{-1}-kW^{-1} for thick aluminum, iron, copper, and lead targets, respectively. The results are compared with the source terms used in the SLAC SHIELD11 code[9-10], which has been used extensively in the shielding design of several electron accelerators. We see that SHIELD11 code over-estimates the source term when targets are composed of low-Z materials and under-estimates the source term when targets are composed of high-Z materials.

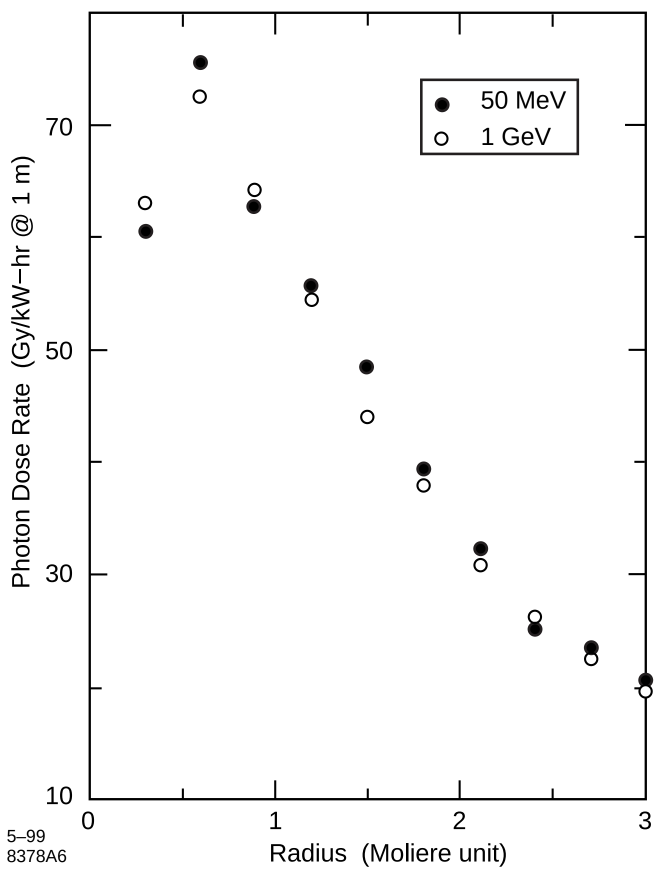

Fig. 6 90^o bremsstrahlung source terms produced in thick lead targets by 50 MeV and 1 GeV e$^-$ beam

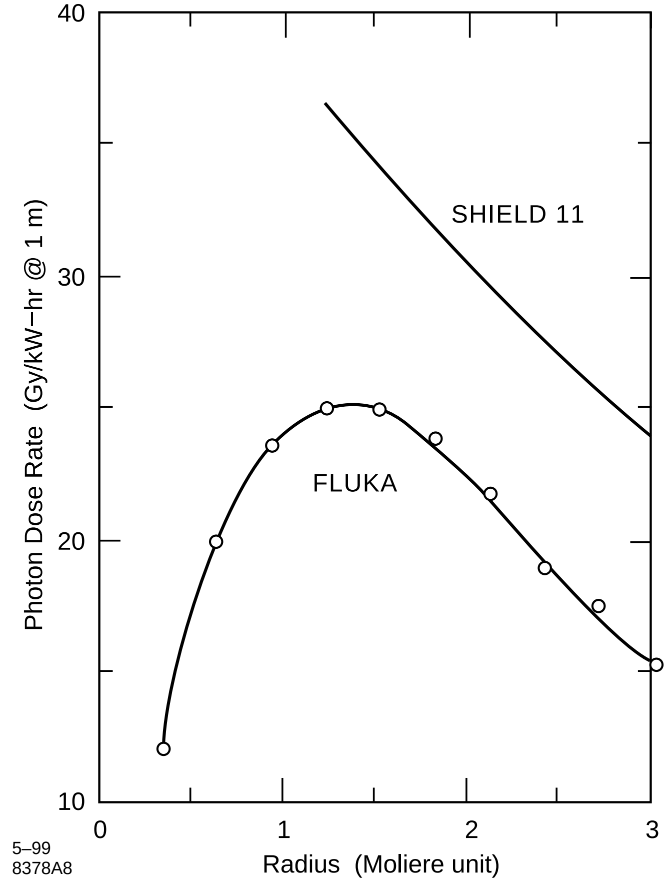

Fig 7. 90^o bremsstrahlung source terms from thick aluminum targets

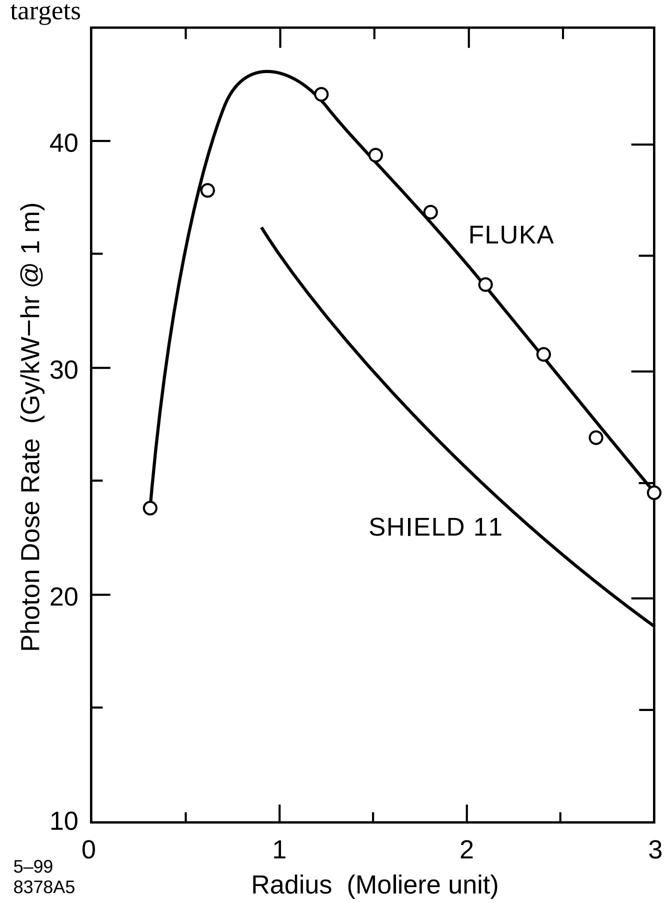

Fig 8. 90^o bremsstrahlung source terms from thick iron targets

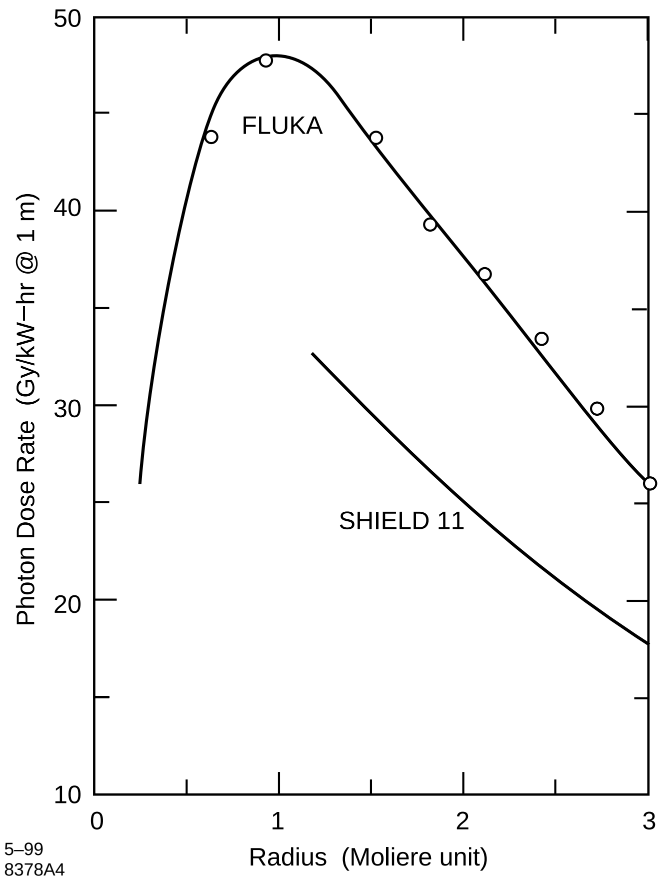

Fig 9. 90° bremsstrahlung source terms from thick copper targets

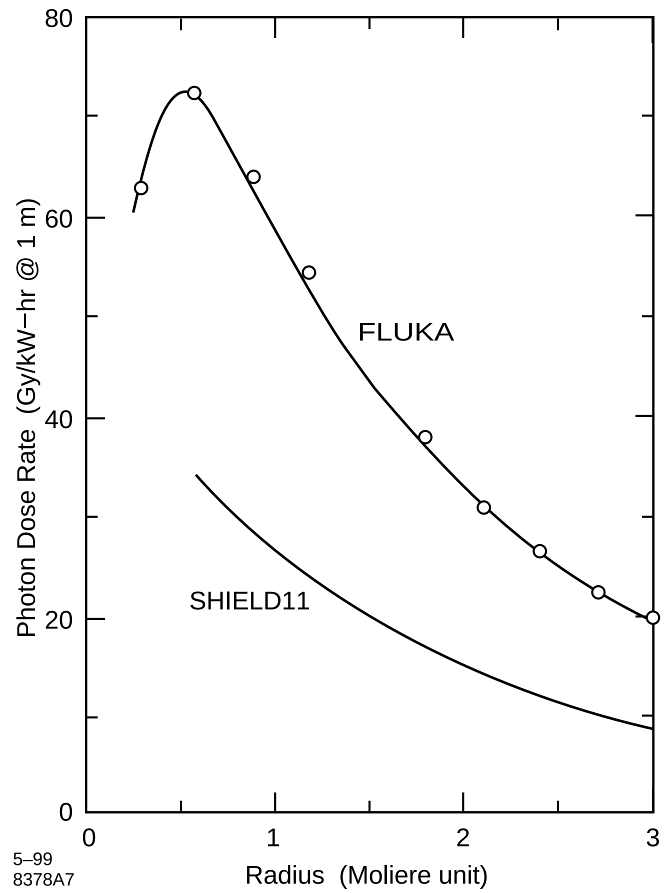

Fig 10. 90° bremsstrahlung source terms from thick lead targets

IV. Conclusion

By using the EGS4 and FLUKA Monte Carlo codes to study 90° bremsstrahlung source terms for thick targets at incident electron energies from 50 MeV to 10 GeV, this work indicates that the source terms, in unit of Gy-m^2-h^{-1}-kW^{-1}, are independent of primary electron energy over the range from 50 MeV to 10 GeV. The source terms for thick aluminum, iron, copper, and lead targets of varying target radii are reported. The results will be of use in modifying the SLAC SHIELD11 code.

Spectral studies showed that 99.9% of the photons have energies smaller than 10 MeV, independent of the incident beam energy. This provides useful information for shielding at 90°. The calculated spectra will be used in further calculations to study the attenuation of the source terms by different materials.

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